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THERMOELECTRIC DEVICES, BEING BLOWN THROUGH WITH A SUBSTANCE IN THE DIRECTION OF HEAT FLOW

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ABSTRACT: Permeable thermoelements in thermoelectric devices being blown through with a substance in the direction of heat flow are described. A battery of this kind of thermoelements can be use in utilizing the heat of combustion products produced in a heat-using facility.

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Making the arms of thermoelements in thermoelectric devices permeable permits modifying their electrical characteristics by changing the temperature profile along the height of an arm by blowing through with a substance in a direction perpendicular to the plane of the junctions. The change in the temperature profile involves change in the thermal currents entering the thermoelement and leaving it. Here we can consider schemes of thermoelectric devices with two flowing directions: opposite to thermal current when the coolant is displaced from the cold junctions of the thermoelectric generator to the hot junctions, produces a temperature drop at them, arrives at the surface with a temperature close to their temperature, and can be used efficiently thereafter; and the direction corresponding with the direction of the thermal current, that is, blowing from hot junctions to cold.

When a thermopile operates in the mode of gas (liquid) coolant, the temperature drop at the junction is produced due to an external power source, and the cooled substance gives off its heat within the thermal element, streaming from the hot junctions to the cold. Here the removal of heat from the hot junctions is mandatory.

When a thermopile operates as an electric generator, the heat carrier blown through the thermoelements gives off heat within the capillaries (pores) and, on exiting at the surfaces of the cold junctions, mixes with the external cooled flow. In this case, cooling of the cold junctions is needed.

This article examines the following operating conditions of a permeable thermoelement (Fig. 1).

A hot heat carrier at t_3 is blown through the capillaries formed in in the thermoelements. The supply of heat here is provided both through the surface of the hot junctions as well as within the capillaries. A battery of these thermoelements can serve for utilizing the heat of combustion products produced in some heat-using facility. The consumption of the heat carrier and its temperature ahead of the battery will be specified.

If we know the geometrical characteristics of thermoelements and the properties of the material (for example, internal resistance r), then for a specified power W that must be used up in external load R we can usually find the required temperature gradient at the junctions ΔT from the following energy balance:

$$\rho v_\infty c_{p_r} K_1 b l (t_3 - t_1) = W + \lambda K b l \left(\frac{dT}{dy}\right)_{y=0} + \Pi_1, \qquad (1)$$

where Π_1 is the Peltier heat given off at the cold junctions [1] .

At the heated side of the thermoelements (for y = δ), there is a heat carrier temperature gradient due to the absorption of Peltier heat at the hot junctions -- Π_2 [1] and due to the removal of heat owing to the thermal conductivity of the arm material, that is,

$$\varrho v_{ж} c_{p_1} K_1 bl (t_3 - t_2) - \Pi_2 = \lambda K bl \left(\frac{dT}{dy}\right)_{y=\delta}. \qquad (2)$$

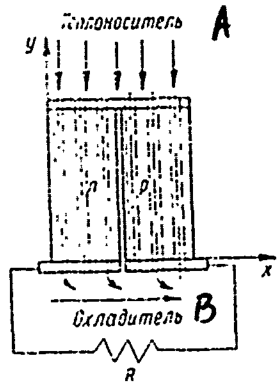

Fig. 1. Working Diagram of Thermoelement

Key: A. Heat carrier
B. Coolant

The temperature gradients at the cold and hot surfaces of the thermoelement are determined from the expression for the temperature distribution along the height of the arm [2].

The temperature of the coolant at the outlet from the capillaries t_1 can be determined from the equation for the distribution of temperatures in the coolant within the thermoelements [2] for y = 0. Neglecting terms of second-order smallness, we get

$$t_1 = T_1 - C + \frac{\left(\frac{B}{A} - \frac{1}{2}\right)\exp\left(B + \frac{A}{2}\right)\delta}{N}\left\{t_2\left(\frac{B}{A} - \frac{1}{2}\right) - T_1\left(\frac{B}{A} - \frac{1}{2}\right) + \Delta T + C\left[(1 + A\delta)\left(\frac{B}{A} + \frac{1}{2}\right) - 1\right]\right\}. \qquad (3)$$

Here

$$A = \frac{4\alpha}{\varrho v_{ж} c_p d}; \quad B = \sqrt{\left(\frac{A}{2}\right)^2 + \frac{4\alpha\Pi}{\lambda d}}; \quad C = \frac{q_{v} d}{4\Pi\alpha}.$$

In thermal generators of this type, it is desirable to keep the temperature of the hot junctions as high as possible, permitting maximum utilization of the heat from the hot heat carrier, by keeping the greatest gradient at the junctions. The maximum temperature of the hot junctions is realized when it is set equal to the heat carrier temperature in the section y = δ, that is, $T_2 = \Delta T + T_1 = t_2$. Solving, with these assumptions, the system of equations (1) -- (3), we can determine the temperatures of the junctions and the coolant at the inlet to the capillaries t_2 and at the outlet from them t_1. Then, we must calculate the cooling system that makes it possible to maintain the required temperature gradient at the junctions in the resulting temperature interval.

As follows from Eq. (1), Peltier heat is removed from the cold junctions by the stream of coolant bathing their surfaces, heat that arrives as a result of the material's thermal conductivity, and the physical heat of the heat carrier leaving at the cold junction surface with temperature t_1.

If it is assumed that the heat transfer coefficient for the case when a heat carrier is blown into the cold stream, is determined on analogy with the case in which a cold substance is blown into a hot stream, the amount of heat removed here can be determined by the expression

$$\alpha_1 (T_1 - t_0)\, bl = \lambda K bl \left(\frac{dT}{dy}\right)_{y=0} + \Pi_1, \qquad (4)$$

where t_0 is the mean temperature of the cooling stream.

From Eqs. (1) and (4) we see that in this determination of the heat transfer coefficient α_1, it is additionally necessary to allow also for the heat imparted to the coolant owing to the physical heat of the mixed heat carrier. When intense blowing past the cold junctions takes place, we can set t_0 unchanged. Then, by assigning the value of T_1 and determining α_1, we can obtain the heat losses from the coolant according to (4).

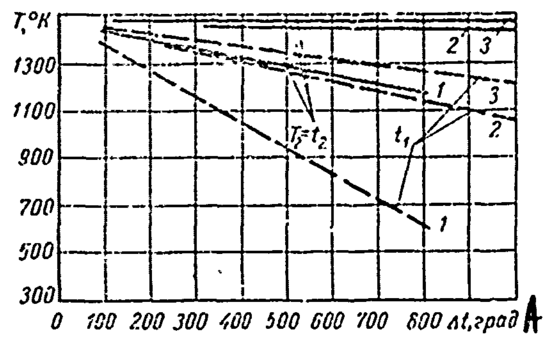

Fig. 2. Dependence of Temperature of Hot Junctions (T_2), Heat Carrier (t_2 and t_1), and Coolant (t_0) on the Temperature Gradiant

1 -- $\rho v_w = 10^{-4}$ kg/cm^2• sec; 2 -- $\rho v_w = 4 \cdot 10^{-4}$ kg/cm^2 • sec;
3 -- $\rho v_w = 8 \cdot 10^{-4}$ kg/cm^2 • sec

Key: A. degrees

Thus, Eqs. (2) - (4) permit a complete thermal calculation of the thermoelectric battery swept with a heat carrier in the direction from the hot junctions to the cold.

Fig. 2 shows the dependence of the temperatures of hot junctions and heat carrier on the temperature gradiant for three different volume flow rates of coolant through the capillaries (0.1 cm in diameter, 25 capillaries/cm^2), built into the thermoelement with mean material characteristics $z = 0.5 \cdot 10^3$ 1/K_1, and $\lambda = 0.01$ w/cm °K. The temperature of the heat carrier in front of the battery and the initial temperature of the coolant are assumed to be $T_3 = 1500$°K and $t_0 = 300$°K.

The effectiveness of permeable and impermeable thermal batteries can be compared by examining specific thermal schemes.

The efficiency of the thermoelectric device is

$$\eta = \frac{Q_1 - Q_{\text{ух.г}} - Q_{\text{т}}}{Q_1},$$

where $Q_1 = \varrho v_0 K_1 c_p b l (t_3 - t_0)$ is the available heat, $Q_{\text{ух.г}} = \varrho v_0 K_1 c_p b l (t_1 - t_0)$ is the heat loss from the exiting gases, and $Q_{\text{т}} = \lambda K b l \left(\frac{dT}{dy}\right)_{y=0}$ is the heat loss from the cold junctions due to the thermal conductivity of the material.

For identical ΔT (nearly identical outputs), the temperature gradient at the cold side of the swept thermoelements, and therefore, the loss of heat due to thermal conductivity from the cold junctions, Q_T, will be considerably greater than in the impermeable battery under otherwise equal conditions.

At the same time, considerably less heat is supplied through the surface of the cold junctions through the permeable battery than through the impermeable battery. The remaining heat arrives via the surface of the capillaries or the pores from the cooling heat carrier. Here the thermodynamic losses from the nonequilibrium heat transfer become less and, while the efficiency calculated in the usual way, from the ratio of the power obtained to the total heat introduced into the material of the thermoelement, is lower than in the battery with solid thermoelements, the exergetic efficiency can be in an inverse relationship with the energy efficiency of the solid generator. Hence, it follows that this kind of permeable thermoelement can be effective in conditions where the exergetic losses are appreciable, for example, when it is required to use restricted amounts of thermal energy contained in the heat carrier at low temperature, for unlimited possibilities of removing heat at the temperature of the medium, as occurs in transport conveyances moving at a corresponding speed in a water or air environment.

The effect of heat losses from the exiting gases on the efficiency of permeable and impermeable thermoelements cannot be determined uniquely. The temperature of the hot junctions of the permeable battery can approach as close as possible to the heat carrier temperature t_3. The heat carrier will leave the battery at a temperature close to the temperature of the cold junctions ($t_{yx.r} \rightarrow t_1$), which obviously is much lower than the temperature of the hot junctions. In a battery with impermeable thermoelements, the hot heat carrier will lower its temperature as it passes along the battery, but even at the outlet its temperature must be higher than the temperature of the hot junctions, ($t_{yx.r} > T_2$).

The intensity of heat transfer in capillaries determined by their diameter and number as well as by the volume flow of the sweeping material strongly affects $Q_{yx.r}$ in the permeable thermoelement. The more intense the internal heat transfer in the capillaries, which can be attained, for example, by reducing their diameter and increasing the amount per unit surface, the smaller will be the difference in the temperatures of the cold junctions and the heat carrier exiting at their surfaces ($t_1 - T_1$), and this means, the smaller also will be $Q_{yx.r}$. Under certain conditions, in permeable thermoelements this temperature difference reduces virtually to zero and the heat loss from the exiting gases, for sufficiently intense cooling of the cold junctions, can be slight, while in a nonswept thermoelement it is determining. Therefore, in swept thermoelements it is possible to attain higher efficiencies than in impermeable thermoelements.

Owing to the presence of a large number of closely interrelated factors affecting the efficiency of permeable thermoelements, it is best to compare them with impermeable thermoelements for specific conditions of the thermal scheme selected.

The symbols are as follows: T and t are the temperatures of junctions and heat carrier, respectively; ρv_w is the mass flow rate of the heat carrier; $G_{вх}$ is the volume flow of coolant at the inlet; b and l are the battery length and width; $K_1 = F_{пор}/F$; $K = (F - F_{пор})/F$, $\Pi = K_1/K$; α_1 is the coefficient of heat transfer from cold junctions to the cooling stream; λ is the coefficient of thermal conductivity of the material of the thermal elements; α is the coefficient of heat transfer within the capillaries; d is the capillary diameter. The subscripts are as follows: 0 stands for coolant, 1 refers to the situation when y = 0; 2 refers to the situation when $y = \delta$.

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